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EXPERIMENTS TO SIMPLIFY FROST SUSCEPTIBILITY TESTING OF SOILS

Chester W. Kaplar

January 1971

CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

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PREFACE

Authority for the investigation reported herein is contained in FY 1964 Instructions and Outline, Military Construction Investigations, Engineering Criteria and Investigations and Studies, Studies of Construction in Areas of Seasonal Frost; Subproject 14, Laboratory Studies of the Effects of Soil Freezing.

The Military Construction Investigations program is conducted for the Directorate of Military Construction, Office of the Chief of Engineers. This investigation was under the technical direction of the Engineering Division of this directorate, Civil Engineering Branch (Mr. F.B. Hennion, Acting Chief).

Mr. C.W. Kaplar, Research Civil Engineer, Applied Research Branch, carried out the study and prepared this report. The investigation was under the general direction of Mr. K.A. Linell, Chief, Experimental Engineering Division, and the immediate direction of Mr. A.F. Wuori, Chief, Applied Research Branch, U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL).

This report was technically reviewed by Mr. Frederick J. Sanger, Special Assistant to the Chief, Experimental Engineering Division, USA CRREL, and by a special review group of the Committee on Frost Action, SGF-C4, of the Highway Research Board, Division of Engineering, National Academy of Sciences.

The author expresses appreciation to Mr. D. Carbee, Civil Engineering Technician, Applied Research Branch, for his valued assistance in conducting the tests and for his suggestions on the improvement of testing equipment and techniques.

Lieutenant Colonel Joseph F. Castro was Commanding Officer/Director of USA CRREL during the publication of this report.

CONTENTS

	Page
Introduction	1
Present frost susceptibility test procedures	2
Approaches to freezing test simplification	4
Modifications of freezing procedure	4
Major problem encountered with freezing cell	6
Multi-ring freezing cell	7
Freezing at constant surface temperature	7
Frost heaving of soils under constant temperature freezing	8
Soils selected for tests	9
Soil preparation procedure	9
Freezing procedure	9
Results of tests	11
Thermoelectric freezing - Peltier battery	17
The projected role of frost susceptibility testing in pavement design practice	19
Conclusions	20
Literature cited	21
Abstract	23

ILLUSTRATIONS

Figure		
1.	Soil freezing cabinet in 40°F coldroom	2
2.	Inside-tapered freezing cell	3
3.	Heave rate versus frost penetration rate	5
4.	Effect of freezing rate on heave rate	5
5.	Multi-ring freezing cell	8
6.	Multi-ring cylinder and inside tapered solid-wall cylinder	10
7.	Frozen specimen in multi-ring cylinder	10
8.	Soils used in tests	11
9.	Heave and frost penetration data for constant temperature tests vs container type	12
10.	Heave and frost penetration data for constant temperature tests vs container type	12
11.	Heave and frost penetration data for constant temperature tests vs container type	13
12.	Heave and frost penetration data for constant temperature tests vs container type	13
13.	Rate of heave vs cabinet air temperature	14
14.	Summary of multi-ring freezing tests	16
15.	Relationship of heave rate and air temperatures for New Hampshire silt in multi-ring containers	16
16.	Experimental setup for freezing soil with thermoelectric cooling unit	18
17.	Silt frozen with a thermoelectric cooling unit in a 40°F environment	18
18.	Cross section of new soil freezing cabinet (2 ft × 2 ft × 5 ft) with self-contained refrigeration	19

CONTENTS (Cont'd)

TABLES

Table Page

I. Typical average load effect due to side friction resistance measured upon ejection of frozen specimens from containers 6

II. Summary of soil characteristics and freezing test results 15

EXPERIMENTS TO SIMPLIFY FROST SUSCEPTIBILITY TESTING OF SOILS

by

Chester W. Kaplar

INTRODUCTION

The selection of suitable soils for use in earth construction where they will be exposed to freezing temperatures is an important function of design. This is especially true and critical in the construction of modern high-speed highways and airfields where any surface roughness due to frost heaving could be detrimental to property and safety. Another very important economic consideration for selection of a suitable material is the prevention of thaw-weakening damage to the costly roadway or runway itself during the spring melting period.

Our present knowledge of soils permits us to recognize quickly the obviously frost-susceptible soils such as silt and clay strictly by visual means. However, to select a nondetrimental material for use as subbase and base course from the assortment of available borrow materials visual means are inadequate. It was firmly established by Taber (1929) and Beskow (1935), further verified by the Corps of Engineers Arctic Construction and Frost Effects Laboratory (ACFEL)*, and has been currently confirmed by the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) that the presence of fines in a soil mass is the most important single factor governing the frost susceptibility characteristics of a soil. Beskow's studies showed that with his test procedure very slight ice segregation was first observable in a sieved soil fraction containing grains between 0.1 and 0.05 mm in diameter. No ice segregation was observed in soil fractions having grains coarser than these. Freezing tests on still finer fractions showed that ice segregation increased further and a very sharp increase was observed for the fraction containing particles 0.01 to 0.005 mm in diameter.

Casagrande (1932), after conducting many freezing experiments in the laboratory and in the field, published his often quoted and used criteria, which related the total percentage of particles finer by weight than the 0.02-mm size in a soil gradation to the possible adverse frost-susceptibility characteristics of the material. The work performed by ACFEL substantiated the general validity of the Casagrande criteria. The ACFEL studies also showed that the 3% finer by weight than 0.02-mm criterion was not a sharp dividing line and that detrimental heaving was possible in some soils with a smaller percentage of material finer by weight than 0.02-mm. The most notable of these were some sandy gravels from Greenland which showed substantial heaving in the laboratory when the quantity finer by weight than the 0.02-mm size was about 1%. On the other hand, some graded gravelly materials may contain 4% or more finer by weight than 0.02-mm and some sandy materials up to 20% finer by weight than 0.02-mm, before showing undesirable frost heave characteristics in laboratory tests.

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* ACFEL was merged with the former Snow, Ice and Permafrost Research Establishment, U.S. Army Corps of Engineers, in 1961, to form USA CRREL.

PRESENT FROST SUSCEPTIBILITY TEST PROCEDURES

A reliable evaluation of the frost-susceptibility characteristics of a soil must be based on some kind of performance test during freezing. One such test was developed for the U.S. Army Corps of Engineers (Linell and Kaplar, 1959; Kaplar, 1965) and has been most useful in the evaluation of soils proposed for use as base course materials at many of the major airfield construction projects in the U.S.A. and overseas. The main control in this test is the rate of frost penetration and the observed effect is the measure of the rate of heaving.

This test has undeniably proved its effectiveness and is prescribed by the Corps of Engineers (Department of the Army, 1965) whenever any doubt exists about the potential frost susceptibility of a soil proposed for use. The major objection to the test is the length of time required for the freezing procedure. Initially (1851) a freezing procedure was adopted requiring that a 6-in.-high specimen be frozen slowly at the rate of ¼ in./day in a specially designed freezing cabinet (Fig. 1). It is obvious that with this procedure 24 days are necessary to completely freeze a 6-in.-high specimen. Subsequently, the freezing rate was increased to ½ in./day or slightly greater with approximately the same results being obtained; freezing time was thus reduced to 12 days or less (Kaplar, 1865). This reduction in testing time is still inadequate to make the test attractive in our need-it-today society.

The laboratory technique used by the U.S. Army Corps of Engineers for a number of years to evaluate the relative frost susceptibility of soils is patterned after techniques used earlier by Taber (1929), Beskow (1935), Casagrande (1932), Winn and Rutledge (1940) and others, except

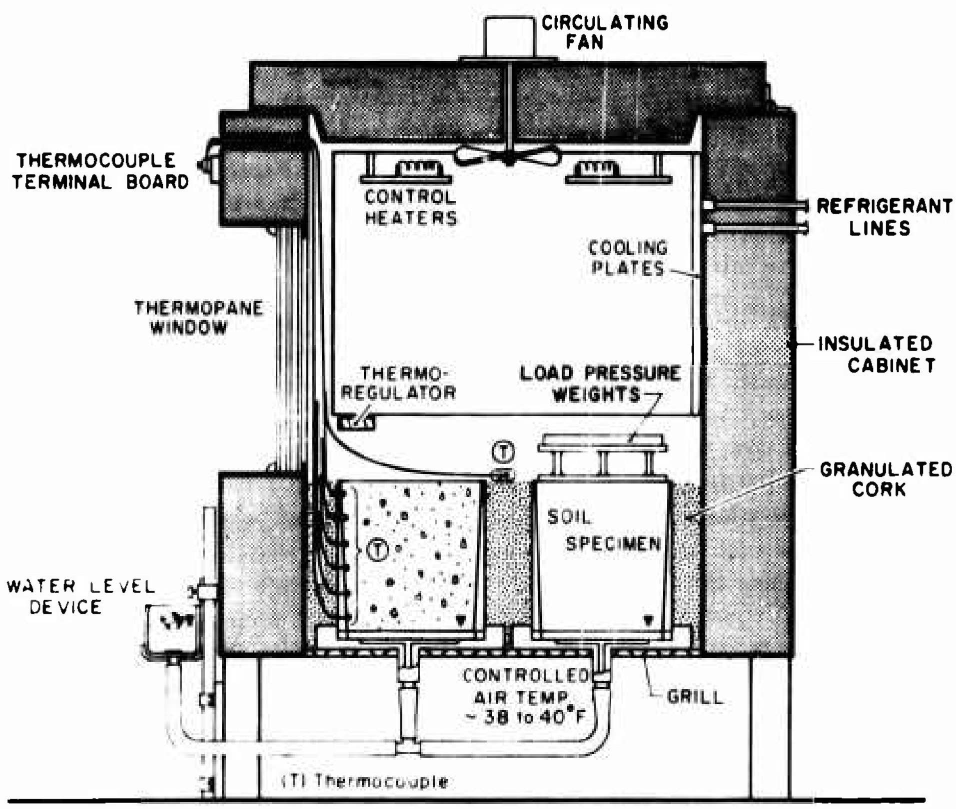


Figure 1. Soil freezing cabinet in 40°F coldroom.

that the Corps of Engineers uses larger (6-in.-diam) specimens. The large-diameter size is essential for evaluation tests on base course soils used in airfield construction.

The specimen containers initially adopted for these tests were waxed cardboard cylinders and later straight-walled polyacrylic (Lucite) tubes because of problems encountered with the cardboard. Subsequently, a completely new Lucite soil cell with a number of improvements was developed; a sketch of this cell is shown in Figure 2. This cell contains a slightly tapered vertical inner wall (¼-in. greater diameter at top) to permit the heaved portion to enter into a wider area and thus reduce wall friction or adfreeze resistance to heaving. The top cover of the freezing cell is removed before freezing is begun.

The evaluation given by this freezing test is empirical in nature. The average rate of heave measured does not represent a simple and fundamental physical value, since such factors as overburden load stress and moisture availability at the plane of freezing vary continuously during the test. Nevertheless, the test results have been useful in 1) the selection of the least frost-susceptible material for construction use when several choices are available, 2) the evaluation of frost potential of in-situ soil or soil previously used for construction, 3) the evaluation of effectiveness of soil additives and treatments in studies of frost inhibitors or modifiers, and 4) the conducting of laboratory studies to determine the effect of various soil parameters on the frost behavior of soils.

Thus, this freezing test is undoubtedly only a first step toward an ultimate rational test procedure that will evolve from the research now in progress at USA CRREL and other laboratories since the basic controlling factors responsible for ice segregation have not been incontrovertibly established.

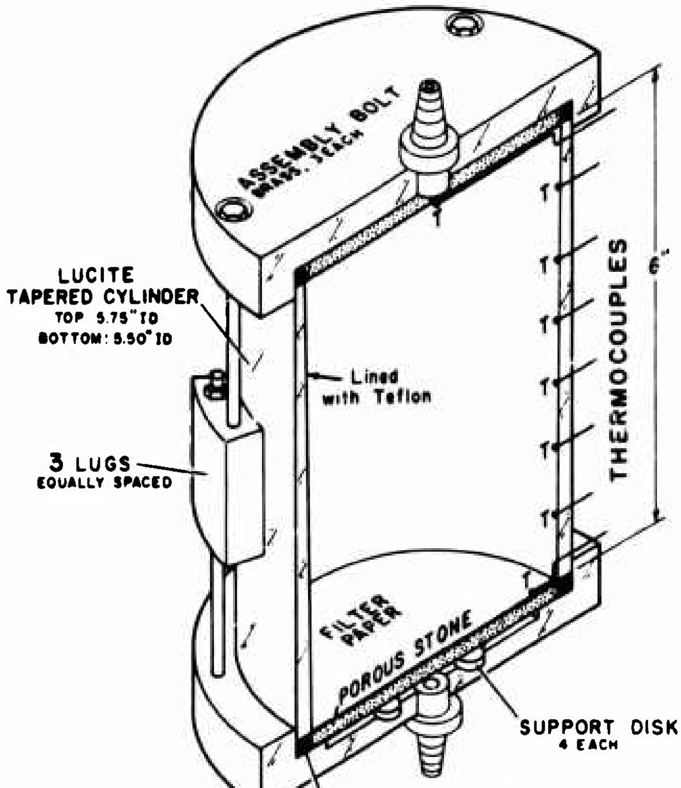


Figure 2. Inside-tapered freezing cell.

APPROACHES TO FREEZING TEST SIMPLIFICATION

For a number of years the author has given considerable thought to various ways of speeding up the frost susceptibility testing of soils by a simplified freezing procedure that would produce visual results easily comprehended and interpreted in terms of heaving rate and ice segregation. Recent experiments have demonstrated that meaningful test results can be obtained by replacing the former slow freezing procedure of ¼ to ½ in./day of frost penetration with a much faster rate of freezing. In these freezing tests, the heaving rate was used as a measure of frost susceptibility. Other improvements in equipment, apparatus and test procedures have made possible increased efficiency and reliability of the test.

Modifications of freezing procedure

Faster freezing rate. In the laboratory freezing test procedures initially developed, a slow rate (about ¼ in./day) of freezing of the soil specimen was considered essential to permit the development of the maximum amount of ice segregation that distinguished the highly frost-susceptible soils from those of lesser frost heaving potential. During these freezing tests the thermostat that controlled the air temperature above the soil specimen had to be manually adjusted daily to produce the desired rate of penetration. The necessary temperatures of the air above the specimens varied because of the different thermal and heave properties of the soils. Therefore, the manipulation of the thermostat depended upon the experience and skill of the technician in guessing how much of a decrement should be obtained to maintain the rate of freezing desired. As a result faster freezing rates were often obtained than were expected; these rates were sometimes as high as ¾ in./day instead of the desired ¼ in./day. However, the average heave rates did not seem to be adversely affected by these relatively large variations in freezing rate, but seemed to have slightly larger values. Consequently, the freezing test procedure was gradually modified to incorporate the slightly faster rates, thus considerably reducing freeze testing time from 24 to 8-12 days.

However, although reduced from 24 to 12 days, testing time still seemed too long in view of the total number of days required to prepare and saturate the specimens, and to process them after freezing. As a result of these early heave rate observations and an apparent demand for further simplification a number of typical soils were selected for experimentation with freezing behavior under more rapid freezing rates, up to 1½ in./day. Thirteen soils were used in the investigation; the data for eleven of these showed that the average heaving rate as measured in millimeters per day increased slightly with the increase in freezing rate. Experimental data for four typical soils are presented in Figure 3. Each shows an increasing response to the faster freezing. The data indicate that the measured heave rates were at least equivalent to or greater than those obtained at slower rates of freezing. This introduced the possibility that perhaps the total testing time might be reduced to considerably less than 12 days.

As a consequence, a limited number of experiments were made on a "dirty" frost-susceptible base course soil (Hutchinson Pit gravelly sand) to observe the effect of fairly rapid freezing rates, up to 8 in./day, on heave rates. The freezing tests were run using the procedures adopted by the Corps of Engineers. All specimens were contained in tapered containers.

The effect of freeze penetration rate on the heave rate for this soil is plotted in Figure 4. The data show that the heave rate (ice segregation rate) increases considerably with faster cooling. From the curve in Figure 4 it appears that there may be a maximum rate, corresponding to a critical freezing rate, beyond which the curve may be expected to drop off until it intersects the theoretical heave rate line computed for expansion of void water only, assuming a saturated soil.

This conjectured behavior at faster freezing rates is what might be reasoned for laboratory specimens of finite height with the physical restraints imposed. It would not apply to natural field

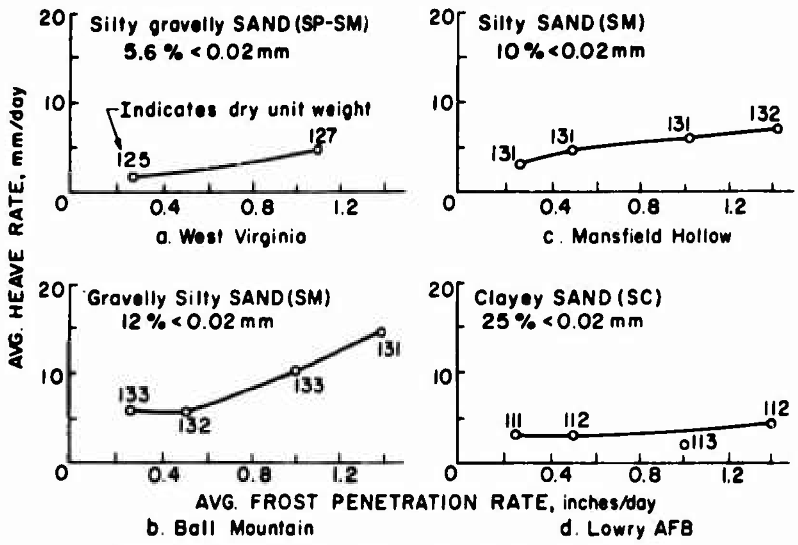


Figure 3. Heave rate versus frost penetration rate.

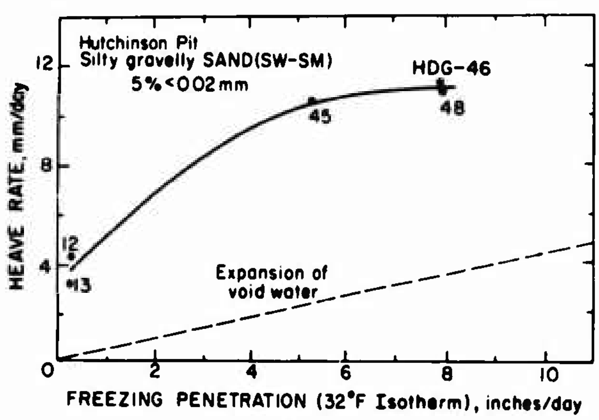


Figure 4. Effect of freezing rate on heave rate. Tests performed in freezing cabinet with manually controlled decreasing temperature schedule and specimens in inside-tapered containers.

situations because of entirely different boundary conditions. The heave rate in a given soil specimen during freezing depends not only on the freezing gradient but on the hydraulic gradient developed below the growing ice lens and on the moisture flow Q from the water reservoir to the freezing plane, according to the expression from soil mechanics $Q = kiat$. The heaving force is believed to originate in the liquid film layer (Martin, 1959; Miller, 1959) that must separate the soil particle from the ice lens. The suction or moisture subpressure is believed to occur as a direct result of the upward movement of the frozen layer; this is analogous to the action of a piston in a hand water pump.

If, under high rates of heat extraction, the liquid film supporting the ice lens cannot be supplied with sufficient water because of soil permeability the free void water will freeze in situ (with accompanying volume expansion) at a greater volumetric rate than that in the liquid films, thus effecting a reduction in void water tension or subpressure and consequently in the flow Q. At very rapid freezing rates (high heat extraction) such that essentially very little time is available for replenishment of load-supporting film water only void water freezes in situ and the maximum theoretical heave rate is reduced to that indicated by the dashed line in Figure 4.

Although limited, the results of rapid freezing experiments indicate that freezing rates might possibly be as high as 6 in./day and still produce useful freezing rate results for frost susceptibility evaluation purposes. At a freezing rate of 6 in./day, useful heave rate data would be available in 24 hours for a 6-in. specimen. At the present state of knowledge such rapid rates of freezing are not recommended for project evaluation without further experimentation to permit observations of replicability and to establish reliability.

The conclusions from these data are:

1. A much faster rate of freezing can be used in laboratory tests to compare the relative frost susceptibility of various soils.

2. The freezing penetration rate of 2 to 3 in./day would reduce freezing time from 12 to 13 days, under the present technique used by the Corps of Engineers, thus permitting a faster response to solution of urgent problems arising in the field during construction. Ultimately the test may be reduced to 1 day or less.

Major problem encountered with freezing cell

A major problem in the freezing tests conducted is believed to be due to the development of sidewall resistance to heaving either by adfreeze of the specimen to the wall of the container or by frictional resistance of the particle contact, or by a combination of both. Efforts have been made by the author to reduce or eliminate this frictional (or adfreeze) resistance which has the effect of an added load on the specimen. Special silicone grease and lapped strips of acetate paper were introduced and finally a tapered cylinder was evolved with a 3-mil-thick, one-piece, adhesive-backed Teflon liner on the inside. Initial data on the force required to eject specimens from the cylinders after freezing indicated that the sidewall resistance problem, although not always eliminated, was considerably reduced by use of the tapered cylinder with silicone grease and lapped acetate strips. Table I presents some of the measurements.

Table I. Typical average load effect due to side friction resistance measured upon ejection of frozen specimens from containers.

Straight-walled cardboard cylinders (psi)	*Straight-walled Lucite cylinders (psi)*	*Tapered Lucite cylinders (psi)*	
3.1	11.5	0	with acetate liner and silicone
4.4	14.2	0	with acetate liner and silicone
0.44	5.8	0	with silicone
2.2	16.4	0	with silicone
0.18	8.9	3.3	with silicone
2.2	7.1	1.2	with silicone
0.8	8.0	0.44	with silicone
3.5		0	with silicone
10.6		0	with silicone
11.5		0	with silicone
11.5			
4.4			
3.5			
0.44			
7.4			

Note: The presence of measurable resistance to specimen removal after test does not necessarily mean that the same frictional resistance was also present during actual freezing. When the specimens were completely frozen they were not immediately removed but were subjected to even colder temperatures to ensure complete freezing for ease of handling, etc.

As data were accumulated and studied, it became more evident that the heave rates were not consistent and that either sidewall resistance was still present to some unknown and variable degree or a problem of water supply existed. Considerable effort was expended on modification of the freezing cell to reduce the possibility of water stoppage. This was done by using coarser porous stones and supporting them on small support disks to provide a comparatively large reservoir beneath so that one large air bubble could not block supply as before (see Fig. 2).

The presence of sidewall resistance was suspected during some previous tests on the coarser sandy and gravelly soils because the heave vs time plots frequently exhibited a flattening out with time as for specimen HDG-63 in Figure 12 in this report. However, this flattening out was not usually observed in the higher-heaving fine-grained soils as shown by the heave data in Figures 9 and 10 for New Hampshire silt contained in the solid-wall tapered cylinders. In computing heave rates for previous tests where heave curves had started to flatten out the flattened portions were disregarded; however, useful test results were obtained from the portion of the curve representing earlier data.

Multi-ring freezing cell

The presence of some restraining force to heaving was verified recently when during a cooperative effort of the University of New Hampshire, the New Hampshire Department of Public Works and Highways, and USA CRREL, UNH reverted to the use of specimen containers made of 1-in.-wide ring segments, such as those used by Taber (1929), Beskow (1955), LaRochelle (1956) and others, to compare results with those obtained using the solid-wall tapered cylinders. The UNH investigators (Biddescombe et al., 1966) found that, for the coarse-grained base course soils they use, higher heave rates were measured in the ring containers for the same test conditions than in the solid-wall tapered containers. The use of rings reduces heaving friction because the ring segments move up with the heaving soil whereas the solid-wall cylinder offers continuous resistance to the upward movement of the frozen soil.

Similar tests performed under the author's supervision at USA CRREL also gave generally similar results on coarse-grained soils. Any freezing test results based on ice segregation rates in rigid walled containers apparently may give lower values influenced by either adfreeze or frictional restraint, or both. For a more reliable test the friction problem must be eliminated.

The multi-ring container is a definite improvement but it has certain drawbacks that for research pruposes may be difficult to overcome. With this container it is difficult to completely or even uniformly saturate the specimen prior to test, difficult to remove the ring to permit splitting of specimen for photographing and determining the water content distribution, and difficult to perform other supplementary tests such as determining the coefficient of permeability during the saturation procedure. However, for gravelly soils that can easily be saturated by soaking under a very small head pressure or by capillarity alone, the use of the rings offers a simple, practical, relatively low friction specimen container for frost susceptibility tests. Tests performed by the author on dirty, sandy-gravelly soil saturated to various degrees, from approximately 60 to 90%, and then allowed to set overnight in contact with water at its base all produced heave rate results comparable with those of the highly presaturated specimens of the same soil.

A sketch of a multi-ring cell made at USA CRREL from ¼-in.-thick polyacrylic tubes and flat plates is shown in Figure 5. Other less expensive materials could be used. The use of top and bottom caps and an outside rubber membrane permits the cell to be vacuumed if desired for better control of degree of saturation in some soils. The use of the caps and rubber membrane facilitate the handling of the specimen. The top cap is removed during freezing, while the bottom one remains as a water reservoir. The membrane may be loosened or removed prior to freezing.

Freezing at constant surface temperature

To overcome some of the objections raised against the controlled penetration rate type of freezing test and some of the non-uniformities of control associated with it, it has been suggested

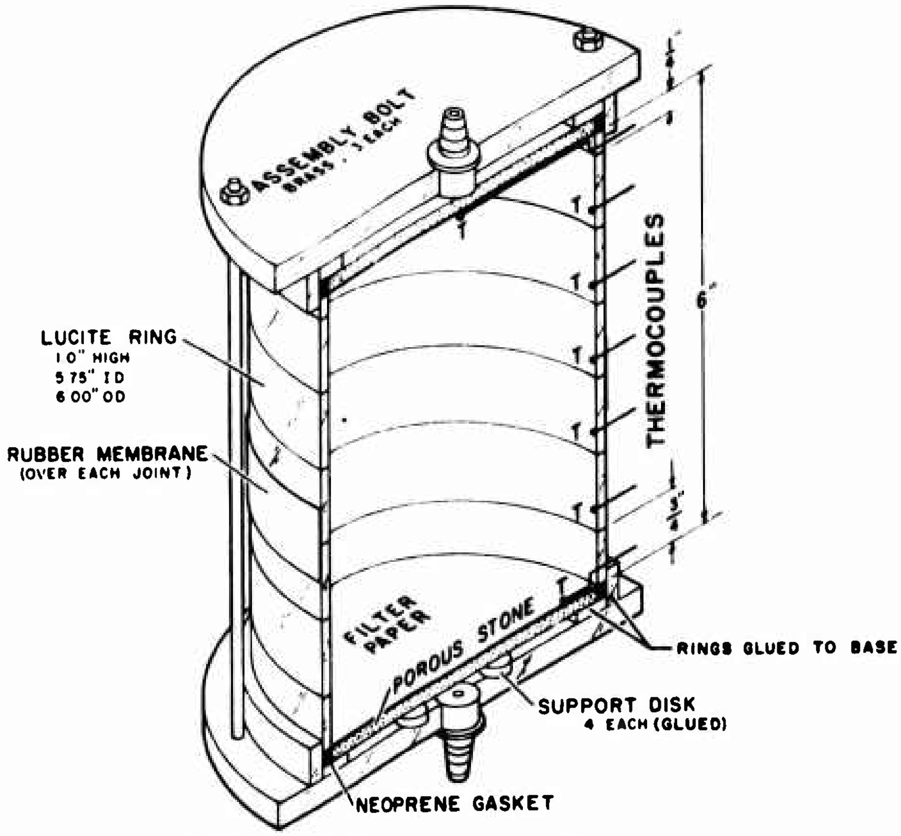


Figure 5. Multi-ring freezing cell.

that perhaps all soil specimens should be exposed to a constant freezing temperature and that the frost heaving behavior of each soil might then be a useful indicator of its relative frost susceptibility. An argument in favor of freezing under a constant temperature is that the imposed boundary conditions in such a procedure would facilitate mathematical analysis of the test results. Mathematical analyses are being conducted at CRREL by Takagi (1965, 1968). The application of a constant freezing temperature would certainly simplify the control problem and would ensure a precise duplication of test conditions for every soil.

Experimentation with this procedure was started by the author at ACFEL. The uniform and consistent heave rate results obtained from these constant-temperature freezing tests were very encouraging. They indicated that useful frost heave data for frost susceptibility evaluation might be obtained in a few days with a much simpler, more easily controllable and reproducible freezing procedure.

More comprehensive freezing experiments were subsequently done using the constant temperature method on a number of soils at different temperatures. Some preliminary experimentation was also done along these lines using thermoelectric cooling, with a Peltier battery.

FROST HEAVING OF SOILS UNDER CONSTANT TEMPERATURE FREEZING

As a result of encouraging indications from preliminary constant-temperature freezing tests, additional tests were made to investigate the effects of various constant temperatures on different types of soils in different types of specimen containers.

Because of the problems of frictional or adfreeze restraint indicated in solid-wall specimen containers, tests were made to compare results from both the multi-ring containers and the solid-wall, Teflon-lined tapered containers. A few tests were made to compare the effects of different ring widths (or heights) in the multi-ring containers; ring widths used were ½ in. and 1 in. The tapered and multi-ring containers with frozen soil specimens are shown in Figures 6 and 7.

The scheduled constant temperatures planned for this series were 25°F, 20°F, 15°F and 10°F. Time did not permit all of these temperature conditions to be applied to all soils but sufficient data were obtained to show some interesting results.

Soils selected for tests

Six soils were selected for comparison of the Teflon-lined tapered cylinders and the multi-ring cylinders: 1) Manchester fine sand, 2) Grantham silty sand, 3) Hutchinson Pit gravelly sand, 4) East Boston glacial till, 5) New Hampshire (Goff's Falls) silt, and 6) Suffield clay. The gradation and other physical properties are shown on Figure 8.

Soil preparation procedure

The tapered soil specimens were molded in special tapered steel molds and placed in the polyacrylic cylinders. The soils for the multi-ring specimens were compacted in the rings which first had been placed and firmly held in a standard California Bearing Ratio (CBR) cylinder. The multi-ring containers consisted of either 1-in. or ½-in.-high polyacrylic rings except the top ring which was ¼ in. high and the bottom ring which was ¾ in. high. The rings were made from 6-in.-diam polyacrylic tubing with ⅛-in.-thick wall to reduce heat conduction upward within the cylinder wall. The ¼-in.-wide top ring was designed so that contact between it and the ring below would be quickly broken by the frost heave forces occurring near the top and thus prevent heat conduction and possible adfreeze problems at some point below. It is believed that high heat conduction through the thicker walled tapered containers was a contributing factor to the sidewall resistance observed in them. A sketch of the multi-ring specimen cell is shown in Figure 5. As indicated the base of the cell is simply glued together from sections of larger acrylic tubing and flat pieces for simplicity and economy.

After compaction of the soil in the rings and removal of the CBR cylinder, the ring specimen was placed on its base and wrapped carefully with dental dam rubber to seal the joints prior to saturation. The highly absorptive soils such as New Hampshire silt were allowed to saturate solely by capillarity. For this material, experiments previously performed at ACFEL showed that the initial degree of saturation at preparation did not affect the freezing heave rate results because silt soils 6 in. high can absorb water overnight by capillarity while tempering. The more impervious and higher density soils were wetted by gradually increasing the hydraulic head from 0 to about 2 ft to induce water to enter the specimen. Small heads were used to minimize the possibility of internal rearrangement of fines that might occur due to application of vacuum and the establishment of a resulting head of up to 33 ft of water pressure. During freezing all specimens were loaded with lead weights to give an overburden pressure of ½ lb/sq in.

Freezing procedure

After saturation specimens were placed in groups of four in a special freezing cabinet, similar to that in Figure 1 except that it did not require a 40°F coldroom. The tubing from the base of the specimens was carefully attached to a constant-level, de-aired water supply, as shown. Air bubbles were carefully prevented from entering the system. A ¼-in.copper plate with the same surface area as the specimen was placed on the specimen surface to prevent drying and to maintain good thermal contact. Four raised lugs on this plate supported the additional weights used to place an overburden load of ½ psi. The space between the specimens was filled with dry

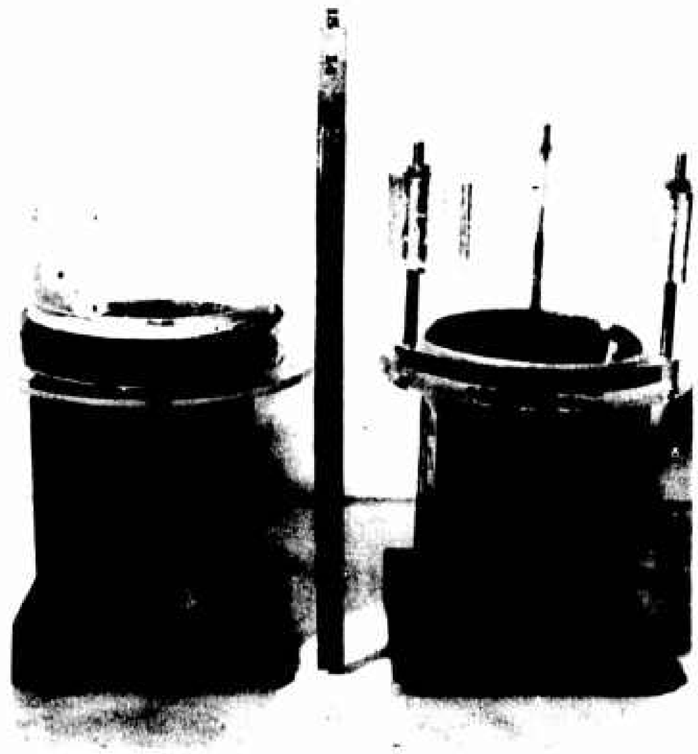
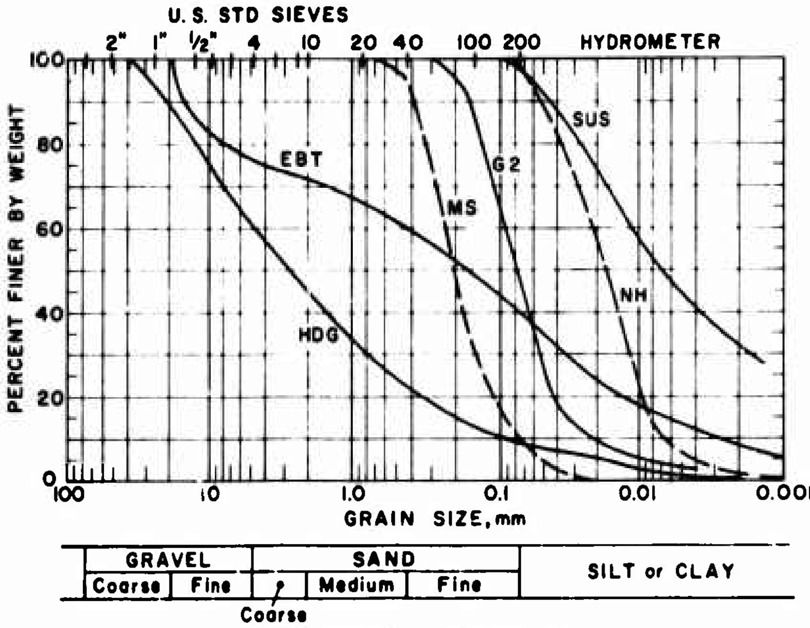


Figure 6. Multi-ring cylinder and inside tapered solid-wall cylinder.

Figure 7. Frozen specimen in multi-ring cylinder.



SOILS USED IN STUDIES

Material	*Symbol*	*Unified soil classification**	*Atterberg limits LL*	*PL*	*PI*
Hutchinson pit gravelly sand	HDG	SW-SM	Non-plastic		
-¾ in. East Boston glacial till	EBT	SC	23	16	7
New Hampshire silt	NH	ML	Non-plastic		
Suffield clay	SUS	CL	35	20	15
Grantham silty sand #2	G2	SP-SM	Non-plastic		
Manchester fine sand	MS	SP	Non-plastic		

* Military Standard 619B (1969).

Figure 8. Soils used in tests.

granular insulation. The specimen was allowed to temper overnight at a cabinet temperature of about 40°F. The following morning the cabinet temperature was lowered to the desired constant temperature and the four ½-in holes in the copper plate were filled with ice water. This was effective in producing crystallization when air temperature dropped below 32°F without the troublesome supercooling and kickback experienced with earlier tests (Haley and Kaplar, 1952). Heaving was measured by dial gauges mounted over each specimen.

In these tests two multi-ring specimens were paired with two tapered specimens for a given run. A number of duplicate specimens were prepared to observe replicability. The duplicate pairs were never tested together but always independently under the same test conditions.

Results of tests

Typical plots of heave versus time for two of the soils at different temperatures are shown in Figure 9-12. In most of these tests the slope of the heave versus time plot is quite uniformly linear, with the multi-ring specimens showing a steeper slope, indicating a larger rate of heave except for two of the gravelly sand specimens (see Fig. 11). The results also indicated that there was no consistent difference in favor of the ½-in.-wide rings and consequently they were eliminated from the remaining tests. There is no obvious explanation for the greater heave rate in specimens HDG61 and HDG65 unless it can be attributed to the slightly larger molding water content. It is also possible that (1) a larger proportion of gravel sizes was present at the bottom of specimen HDG66, restricting the availability of water to the freezing front, and/or (2) a large undetected air bubble was beneath the porous stone of this sample.

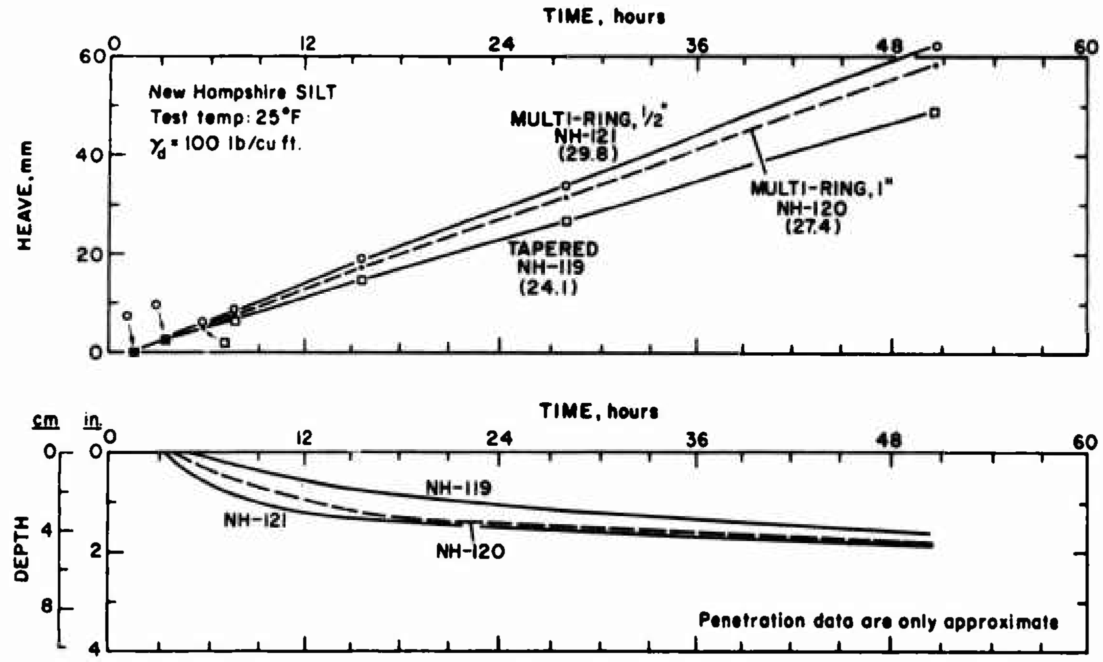


Figure 9. Heave and frost penetration data for constant temperature tests vs container type. Figures in parentheses are the maximum heave rates in mm/day.

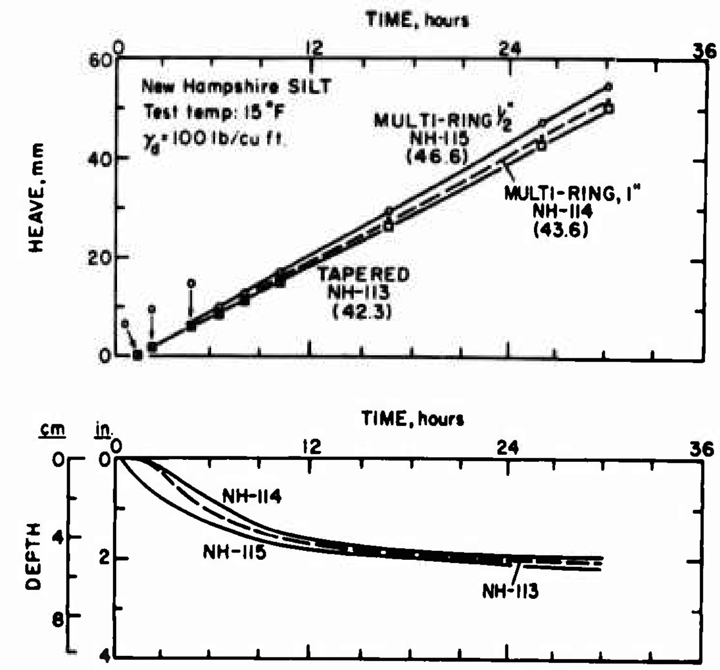


Figure 10. Heave and frost penetration data for constant temperature tests vs container type.

Figures in parentheses are the maximum heave rates in mm/day.

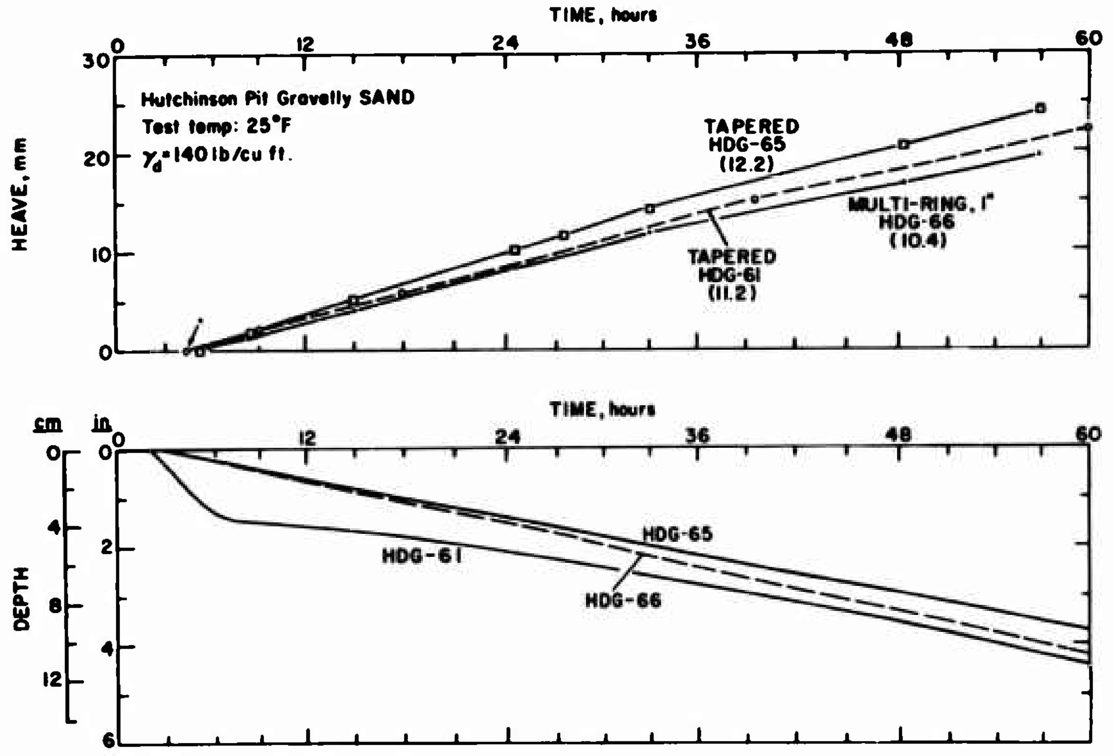


Figure 11. Heave and frost penetration data for constant temperature tests vs container type. Figures in parentheses are the maximum heave rates in mm/day.

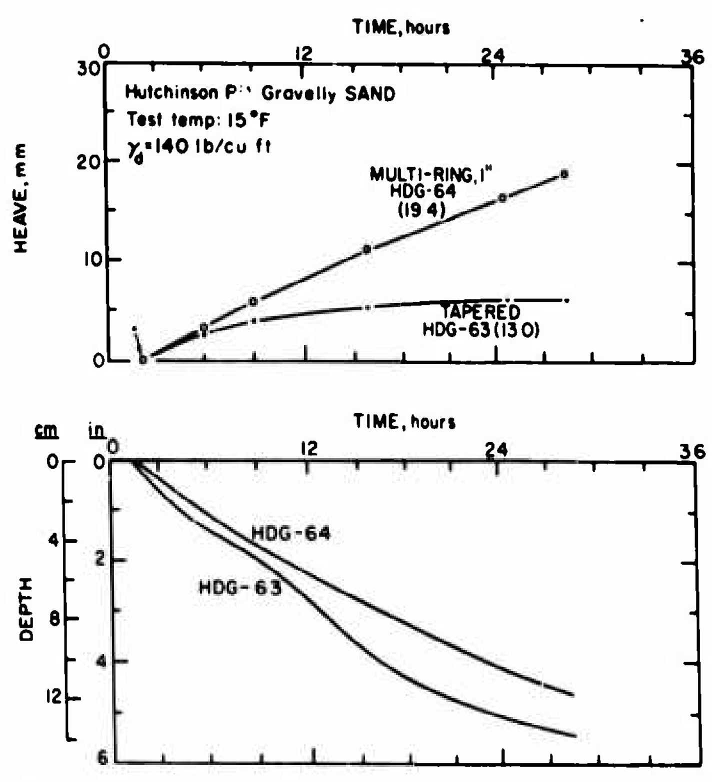


Figure 12. Heave and frost penetration data for constant temperature tests vs container type.

Figures in parentheses are the maximum heave rates in mm/day.

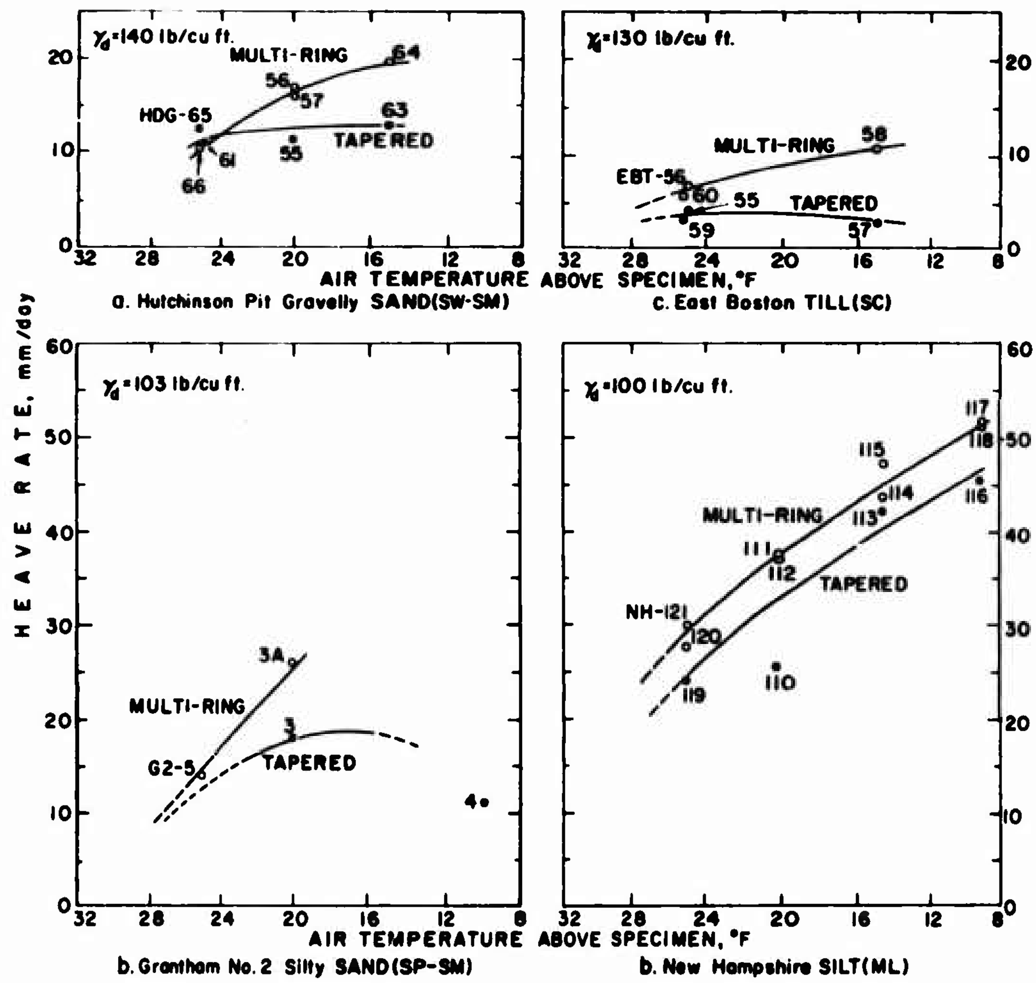


Figure 13. Rate of heave vs cabinet air temperature.

Figure 13 gives the maximum heave rates versus the applied surface air temperatures for four of the soils frozen at more than one constant temperature. Here, too, nearly all the specimens in tapered cylinders exhibited lower heave rates, under the same temperature conditions, than the multi-ring specimens. When duplicate specimens were used the replicate results were in extremely good agreement for both the tapered containers and the multi-ring containers. A summary of the soil characteristics and freezing test results is presented in Table II.

Figure 14 gives a summary of measured heave rates versus the air temperature above the soil specimens used in this series in multi-ring containers. The data obtained are sufficiently well defined to permit a curve to be drawn relating the rate of heaving to the constant temperatures being applied to the surface.

Figure 15 gives a summary of heave rates vs time for New Hampshire silt specimens in multi-ring containers for all four of the temperatures used. The similar freezing depths for these specimens are attributed to the increased heat energy (latent and sensible heat) supplied at the freezing front by the increased water flow rates.

Table II. Summary of soil characteristics and freezing test results.

Speci-men	Type of cylinder	Density (lb/cu ft)	Void ratio	Molding water content (%)	Deg. of saturation* (%)	Constant test temp. (°F)	Approx. days in test	Max. heave rate (mm/day)	Final depth of pen. (in.)
New Hampshire Silt									
NH-119	Tapered †	99.6	0.69	12.1		+25	3.0	24.1	1.7
NH-120	Multi-ring 1 in.	99.8	0.67	12.1	91.9	+25	3.0	27.4	1.7
NH-121	Multi-ring ½ in	99.7	0.67	12.1	88.6	+25	3.0	29.8	1-8
NH-110	Tapered †	99.7	0.67	12.9	99.0	+20	0.3**	25.3	
NH-111	Multi-ring 1 in	98.4	0.69	12.9	99.0	+20	0.3**	37.2	
NH-112	Multi-ring ½ in.	99.1	0.68	12.9	99.0	+20	0.3**	36.8	
NH-113	Tapered †	99.9	0.66	13.6		+15	1.25	42.3	2.0
NH-114	Multi-ring 1 in.	99.6	0.67	13.6	92.4	+15	1.25	43.6	1.9
NH-115	Multi-ring ½ in.	99.5	0.67	13.6	94.4	+15	1.25	46.6	2.1
NH-116	Tapered †	99.9	0.66	13.6		+10	1.1	45.2	1.9
NH-117	Multi-ring 1 in.	99.8	0.67	13.6		+10	1.1	51.4	1.9
NH-118	Multi-ring ½ in.	100.0	0.66	13.6		+10	1.1	51.0	1.9
Suffield Clay									
SUS-1A	Multi-ring 1 in	81.8	1.07	11.7	83.2	+20	2.0	14.2	4.0
Hutchinson Pit Gravelly Sand									
HDG-61	Tapered †	139.8	0.18	5.3	85.5	+25	3.0	11.2	4.5
HDG-65	Tapered †	139.6	0.18	5.4		+25	2.4	12.2	3.5
HDG-66	Multi-ring 1 in.	139.7	0.18	5.2		+25	2.4	10.4	4.0
HDG-55	Tapered †	139.7	0.18	5.2		+20	2.0	11.5	6.0
HDG-56	Multi-ring 1 in.	139.7	0.18	5.2		+20	2.0	16.9	6.0
HDG-57	Multi-ring ½ in.	139.7	0.18	5.2		+20	2.0	16.2	6.0
HDG-63	Tapered †	139.8	0.18	5.2		+15	1.3	13.0	5.5
HDG-64	Multi-ring 1 in.	139.8	0.18	5.1		+15	1.3	19.4	4.5
Grantham No. 2 Sand									
G2-5	Multi-ring 1 in.	103.0	0.61	4.4		+25	2.0	14.1	4.0
G2-3	Tapered †	103.8	0.60	15.0		+20	0.7	17.8	3.6
G2-3A	Multi-ring 1 in.	104.5	0.59	14.2		+20	0.7	26.1	3.7
G2-4	Tapered †	103.5	0.60	4.4		+10	1.2	11.1	6.0
East Boston Till									
EBT-55	Tapered †	129.6	0.28	8.0		+25	3.0	3.8	3.6
EBT-59	Tapered †	129.3	0.27	8.2		+25	2.4	3.3	2.9
EBT-56	Multi-ring 1 in.	129.8	0.28	7.8		+25	3.0	6.4	5.5
EBT-60	Multi-ring 1 in.	129.2	0.27	8.1		+25	2.4	5.6	2.5
EBT-57	Tapered †	129.5	0.28	7.8		+15	1.2	2.7	4.7
EBT-58	Multi-ring 1 in	129.9	0.28	7.7		+15	1.2	10.4	4.4
Manchester Fine Sand									
MS-1	Tapered (Acetate strips)	104.4	0.62	0		+20	2.7	<0.1	6.0
MS-2	Multi-ring 1 in.	100.3	0.69	8.5		+20	1.3	1.4	6.0

* Where no data are given for degree of saturation no measurements were made. It was felt from experience that saturation was 85% or greater.

† Teflon lined.

** Fan failed at 8 hours; test data valid only up to this point.

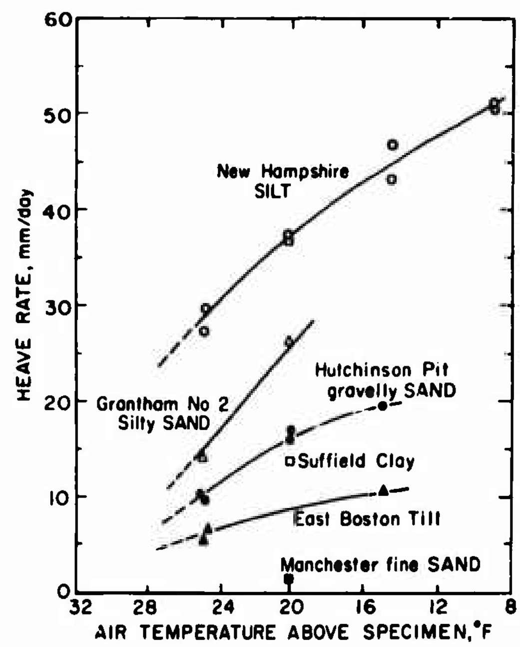


Figure 14. Summary of multi-ring freezing tests.

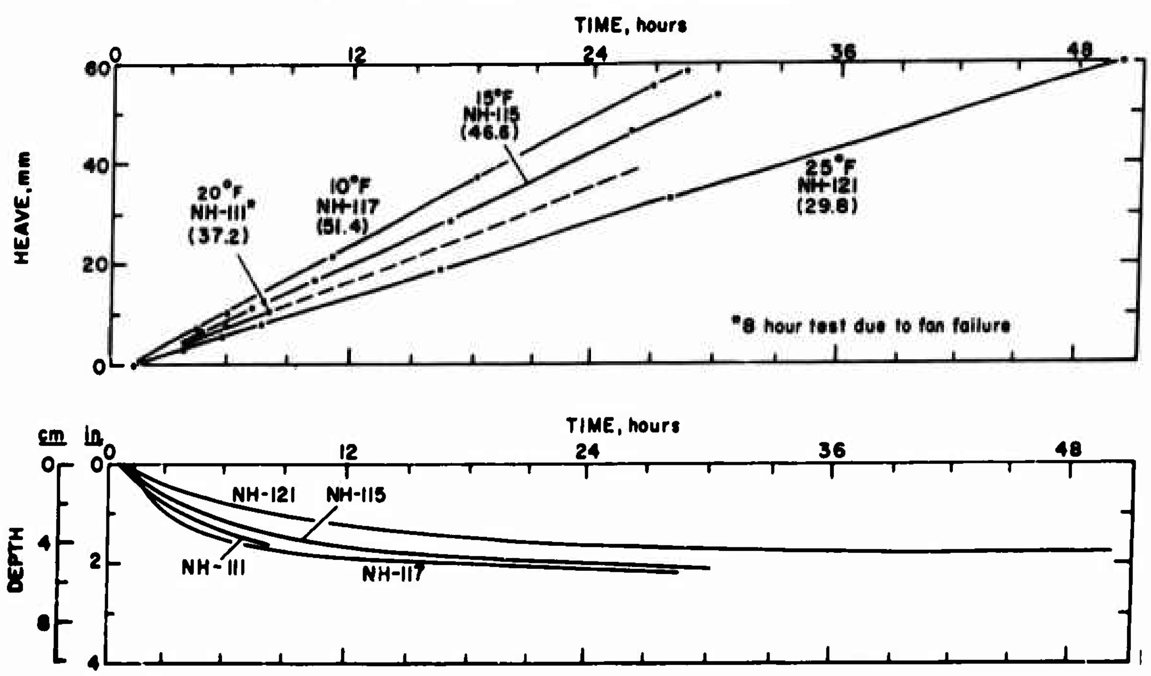


Figure 15. Relationship of heave rate and air temperatures for New Hampshire silt in multi-ring containers. Figures in parentheses are the maximum heave rates in mm/day.

It is evident from the data presented that for the specific conditions of these tests, the rate of heaving increases with decreasing air temperature above the soil (probably up to some critical rate depending on the availability of water to the freezing plane). The increase in heave rate is attributed to the greater driving force of the steeper temperature gradient. The resulting increase in the freezing of water molecules in the liquid film layer between the ice and the soil particles

provides greater energy for heave forces and development of a greater void water suction gradient to increase water flow to the freezing plane. Another possible explanation for the increase of heave rate with increased heat extraction is that the rate of formation of air bubbles out of solution is greatly retarded and the air bubbles that do form at the ice front are quickly engulfed and carried upward in the growing ice. The author has observed that ice lenses in slowly frozen soils usually contain very numerous highly concentrated vertical streamers of extremely tiny air bubbles which are not so discernible in rapidly frozen soils with high heave rates.

These tests further demonstrate that useful data for evaluation of the relative frost susceptibility of soils can be obtained in a much shorter period (two days or less freezing time) by application of a constant subfreezing temperature to representative specimens in friction-free containers.

THERMOELECTRIC FREEZING - PELTIER BATTERY

One attempt to simplify frost-susceptibility freezing test procedure was made by USA CRREL while investigating ways to simplify equipment and reduce testing time. When the Peltier battery was introduced on the market a few years ago in a suitable form and size for use in a soils laboratory a number of exploratory experiments were begun to determine the battery's capability for freezing soils.

Results of a preliminary study performed in early 1964 under the direction of the author indicated that this battery exhibited considerable potential but the freezing technique needed further development. The application of thermoelectric freezing of soils has been studied intermittently since then as time has permitted to develop a bench-type automatic system with specimen container, temperature and heave sensors, and miniature recorders. A typical bench setup is shown in Figure 16. Figure 17 shows silt soil frozen with a thermoelectric battery.

The Peltier principle has been known for some time. It was described by Seebeck and Peltier in 1822 and has been dormant until a few years ago when modern advances in semiconductors made possible the joining of dissimilar metals in such a manner that one surface could be cooled and another heated when a direct current was passed through the system. This is the opposite of the thermocouple principle whereby two junctions of dissimilar metals in a closed circuit are placed at different temperatures and a current is generated through the system by the induced EMF.

The application of the Peltier battery to soil freezing experiments has some very interesting possibilities and should be utilized to its best advantage. It is not considered that it will economically displace all of the functions that a simply constructed convected-air-type freezing cabinet can perform. For example, a single Peltier battery will not be economical in applying the same temperature environment for a group (four 6-in.-diam specimens), or a tray of smaller specimens; and it will not be economical for freezing very large specimens, or for many other special conditions for which the standard freezing cabinets will most likely be more suitable.

The Peltier battery's greatest potential is its portability, mechanical simplicity and constant rate of heat removal; therefore, it promises to be an important tool in conducting small-scale bench-type freezing experiments.

Some of the disadvantages of a Peltier battery, based on the author's experience, may be of interest to potential users: 1. High cost (about $500) of a single unit of battery and need for constant power supply for use on one specimen at a time. 2. Possibility of uneven temperature distribution across the battery's face plate, due to quality control problems in the manufacturing process, thus causing uneven heaving and heave measurement problems. 3. Need for a temperature controlled room (not always available). 4. Limited capability. At CRREL it was impossible to freeze a highly frost-susceptible silt more than a fraction of an inch with a 90-watt capacity cell at ambient temperature in a controlled temperature environment (air conditioned room) even though

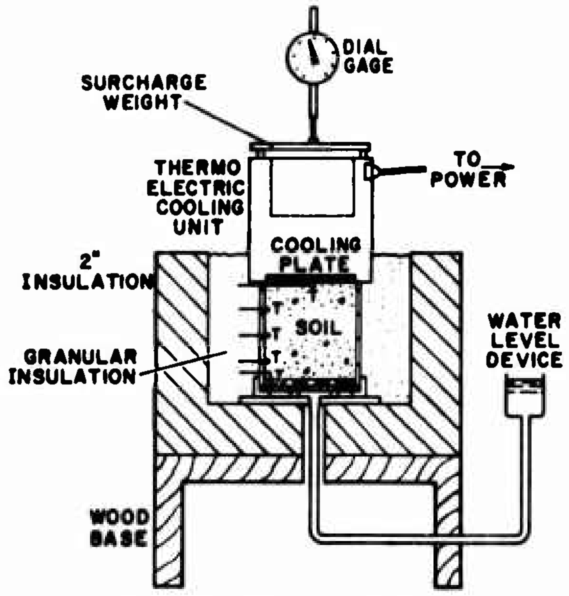


Figure 16. Experimental setup for freezing soil with thermoelectric cooling unit.

Figure 17. Silt frozen with a thermoelectric cooling unit in a 40°F environment.

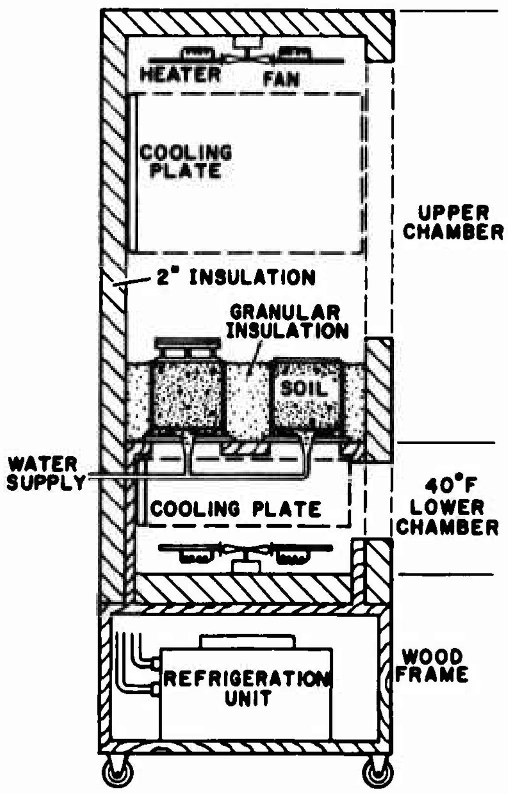


Figure 18. Cross section of new soil freezing cabinet (2 ft × 2 ft × 5 ft) with self-contained refrigeration.

the specimen was completely insulated. It was necessary to place the freezing unit with the soil specimen in a 40°F coldroom before substantial freezing of the silt could be accomplished. 5. Indeterminate useful life. Experience at CRREL has shown that some thermoelectric cooling units have burned out and have had to be replaced within a year.

The author believes that for general purposes a freezing cabinet that can hold four or more specimens at a time offers greater advantages of economy, reliability, and versatility at less cost than several thermoelectric cooling units with equal capacity. A freezing cabinet made chiefly of rigid foamed insulation and containing cooling plates in both upper and lower chambers is currently being redesigned at CRREL so that it may be constructed for about $1,200 to $1,500. A sketch is shown in Figure 18.

THE PROJECTED ROLE OF FROST SUSCEPTIBILITY TESTING IN PAVEMENT DESIGN PRACTICE

With the simpler procedures and shorter testing time requirements outlined in this report, and an economical freezing cabinet of the type described, it should be within the economic means of state highway departments and other organizations to conduct frost susceptibility evaluation tests on every material of potential use in pavement construction, whether base, subbase, or subgrade.

Frost susceptibility testing can be most helpful in the areas indicated:

1. *Selection of suitable borrow sources.* It is necessary that locations of suitable materials be identified during the design stages of a pavement construction project and certainly well in advance of the final detailed design of the pavement.

2. *Optimal utilization of borderline soils.* A more detailed study of soils determined to be of "borderline" frost susceptibility may reveal conditions under which they can be utilized in a roadway system. For example, a load or overburden pressure has been observed to cause significant reductions in frost heaving in laboratory tests (Linell and Kaplar, 1959). Field experiments have verified the laboratory observations (Aitken, in prep.). An allowance for this effect is incorporated in the U.S. Army Corps of Engineers procedure for frost design of pavements, with respect to subgrade heave. A difference of even 2 psi overburden pressure may reduce heaving to tolerable proportions in coarse granular soils and utilization of such a soil at a depth of 2 ft or more below grade might be a practical solution in locations where better soils are scarce. Only testing under variable loads can establish the load pressure-heaving relationship for different soils with our present state of knowledge.

3. *Field control during construction.* Subgrades and borrow pits are seldom uniform throughout and with proper inspection practices it should be possible to assess promptly the suitability of any variable material in sufficient time to allow optimal disposition without incurring major delays.

It is apparent from the foregoing discussion that the evaluation of the relative frost susceptibility of a soil can be used for more than merely borrow selection. By means of the freezing test under simulated conditions of overburden load, density and depth to free water availability, the best utilization can be made of many materials that might possibly be considered unsuitable because of a lack of better understanding of their performance characteristics. With the availability of a simpler and quicker procedure of freezing under constant temperature, and the availability of suitable freezing equipment for multi-specimen testing at one time, useful and long-needed data can readily be obtained to assist the highway designer and engineer to do a still better job.

The problem of standardization of the heave testing of soils might properly be considered at this point. It has been shown in this report that, for the special conditions of the tests reported, heaving response of soil is proportional to the driving force, i.e., temperature gradient, or heat extraction rate. Because of this, the question arises regarding the best freezing temperature to be used in frost susceptibility testing of soils. There is no ready answer at the moment. It is recommended that highway department laboratories wishing to perform such tests should obtain heave rate data at more than one heat extraction rate to obtain a better understanding of the potential behavior of their soils under any variable winter conditions in their localities.

Considerable research still needs to be done to answer the many questions arising from work that has been accomplished and presented in this report and in other reports, on the frost problem in soils. It is believed that our knowledge in this area has considerably improved in the past few years and research now underway in a number of places should produce even more interesting and useful results. It is not believed, however, that with the present state of the art we are ready for the standardization of the frost susceptibility testing of soils.

CONCLUSIONS

Laboratory studies indicate that the slower procedures previously used for frost susceptibility testing by freezing can be speeded up considerably. Experimental data on several different soil types reveal that ice segregation rate is a function of the rate of h at extraction as governed by surface temperature.

Observation of heave rate data in different soil containers in this study and others indicates that the problem of sidewall friction is of paramount importance, especially when rigid containers are used. Useful and replicable results were obtained with multi-ring containers. Unless means can be found to eliminate the friction or adfreeze problem on rigid wall containers, frost heaving evaluation by freezing should be performed under relatively friction-free conditions.

Observations and results obtained from freezing tests at constant temperatures indicate that frost testing time can now be reduced to not more than a few days, including specimen preparation time, to produce useful information. The freezing cabinets with a capacity of four 6-in.-diam specimens are considered the most suitable and economical means for batch output required for engineering support. Testing in duplicate pairs, as a minimum requirement, is recommended in view of the importance of decisions to be made on the basis of test results.

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13. ABSTRACT

Experiments conducted at USA CRREL in recent years indicate that the two weeks or so required for the frost susceptibility testing of soils with previous procedures can be shortened considerably. Results of these experiments show that useful frost heaving data can be obtained in a matter of 2 or 3 days by a more rapid freezing technique. Results of experiments in which soil specimens were exposed to a constantly maintained temperature are presented. Data show that heave rate in laboratory experiments is a variable, not a constant, of a soil and is strongly dependent upon the heat extraction rate. The important role of frost susceptibility testing and soil evaluation for highway design is discussed. The suitability of equipment for use in conducting frost-heaving tests is also discussed.

14. KEY WORDS

Frost heave
Frost susceptibility tests
Frozen soil tests
Soil freezing tests
Temperature control

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